Docket No. 2003-074-DSK

OPTICAL POWER DISTRIBUTION MANAGEMENT AND APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention:

The present invention relates generally to an optical illuminator system, and in particular, to a distribution management and method for delivering optical power to a plurality of optical data devices.

2. Background of the Invention:

Optical power management systems typically require the use of at least one optical power source (e.g., a CW laser, pulsed laser, laser diode, light emitting diode, etc.) for recording, retrieving and manipulating data. Small, relatively low power, low cost solid-state laser diodes with modest optical coherence are the predominant source of optical illumination in existing optical data storage systems. However, the need for shorter wavelength sources to enable greater data storage densities, the need for more powerful sources to enable increased data transfer rates, and the need for sources with longer coherence lengths for holographic data storage and other coherent applications, give rise to the problem of accommodating physically larger, higher power dissipating sources within the limited form factor of an optical device. Further compounding the problem are budgetary constraints that place a limit on the optical source cost per optical data device and the need for a highly reliable source.

Lower power, lower quality sources (i.e., sources with higher relative intensity noise, lower coherence length, higher wavelength drift, higher temperature sensitivity, limited wavelength tunability, etc.) limit the performance of optical storage drives and other optical data devices that use optical illumination (e.g., optical data replicators, fast optical search devices, etc.). This performance limitation is a consequence of the trade-off between the total energy required to achieve a desired physical and/or chemical effect while manipulating (e.g., recording, retrieving, processing or copying) data over a given illuminated area, and the time it takes to deliver the required energy. As such, this performance limitation represents a limitation on the optical data device parameters, including data density, capacity, transfer rates, search rates, error rates, integrity, reliability and lifetime.

Therefore, it would be desirable to have a system and method for efficiently utilizing a superior laser source despite its larger physical size, increased power and/or cooling demands and greater cost. It would be even more advantageous if such a system and method were capable of automatically detecting and correcting for optical power defects and failures, and optimizing the lifetime of laser sources - all with minimum user intervention. Finally, such a system and method could provide optical power on demand, boosting the performance of optical data devices that received higher performance priority.

SUMMARY OF THE INVENTION

The present invention provides a method, apparatus and computer program for managing the distribution of optical power from a plurality of (1 to M), high quality, high power optical sources, to a plurality of (1 to N) optical data devices. The optical data devices can be data storage drives, data search engines, data replicators, or other components that use optical power for their operation. Also, the present invention provides a data management system with the increased flexibility of monitoring and redirecting optical power on demand, which increases the fault-tolerance and performance (e.g., through higher data transfer rates) of the data management system.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

Figure 1 depicts a block diagram illustrating a fault-tolerant, optical power distribution and management system in accordance with a preferred embodiment of the present invention;

Figure 2 depicts a pictorial representation of an exemplary optical power switch and tunable coupler module that may be used to illustrate principles of the present invention;

Figure 3 depicts a pictorial representation of an exemplary generic optical power switch and tunable coupler module that may be used to illustrate principles of the present invention;

Figure 4 depicts a flowchart of an exemplary process for an optical power monitor to manage the distribution of power levels for a plurality of data devices, in accordance with a preferred embodiment of the present invention;

Figure 5 depicts a pictorial representation of an exemplary equipment rack containing optical data devices, optical power sources, a laser power monitor, and an optical power switch and tunable coupler module, in

accordance with a preferred embodiment of the present invention; and

Figure 6 depicts a pictorial representation of an exemplary data management system containing multiple interconnected racks similar to the exemplary equipment rack depicted`in **Figure 5**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference now to the figures, and in particular with reference to **Figure 1**, a block diagram of a fault-tolerant, optical power distribution and management system is illustrated in accordance with a preferred embodiment of the present invention. Exemplary system **100** includes a plurality of optical power sources which, in this case, are laser power sources **102a-102m** (e.g., where "m" denotes the final or m^{th} laser power source). Each laser power source **102a-102m** includes a power output connection **103a-103m** and power monitor output connection **105a-105m**. Power output connections **103a-103m** are coupled to respective inputs of optical power switch and tunable coupler **104**, and power monitor output connections **105a-105m** are coupled to respective inputs of laser power monitor **108**. Each power output connection **103a-103m** couples the output power of the respective laser power source **102a-102m** to optical power switch and tunable coupler **104**. Each power monitor output connection **105a-105m** relays an electronic signal to laser power monitor **108** that is proportional to the intensity of the respective laser power source **102a-102n**. Such a signal is derived from the detection of a small sample of the laser power. Connection **113** couples power redirection signals from laser power monitor **108** to optical power switch and tunable coupler **104**.

Exemplary system **100** also includes a plurality of optical data devices **106a-106n** (where "n" denotes the final or nth optical data device). Power output

connections **114a-114n** couple the output power of the respective laser power sources **102a-102m** from optical power switch and tunable coupler **104** to selected inputs of optical data devices **106a-106n**. As described in more detail below, the actual power levels at output power connections **114a-114n**, and the selection of inputs to optical data devices **106a-106n** are performed by optical power switch and tunable coupler **104**, which may select the coupling ratios based on an algorithm, or which may simply use a predetermined coupling ratio.

Power monitor output connections **107a-107n** of respective optical data devices **106a-106n** are electronically relayed to respective inputs of laser power monitor **108**. Each power monitor output connection **107a-107n** couples a relatively small percentage of the laser source power received at the respective optical data device **106a-106n** to a photodetector that converts the received intensity into an electronic signal which is then transmitted to laser power monitor **108**. Data connections **116a-116n** transfer data (e.g., storing and retrieving) between optical data devices **106a-106n** and respective input/output (I/O) connections of data management system controller **110**. Output connection **111** of laser power monitor **108** couples fault alert signals (e.g., if any laser power level errors occur) to an input of data management system controller **110**. Output connection **112** of data management system controller **110** couples performance priority signals to an input of laser power monitor **108**.

Essentially, laser power sources **102a-102m** and optical data devices **106a-106n** can be mounted on the same equipment rack, where laser sources **102a-102n**, optical data devices **106a-106n**, and laser power monitor **108** and optical power switch and tunable coupler **104** modules use a similar form-factor in order to facilitate the field replacement of defective units, the upgrade of existing equipment, and the inclusion of additional equipment (e.g., more laser sources, new optical data devices, etc.). Preferably, more than one each module should be available in order to provide the system with the redundancy required for superior fault-tolerance.

Alternatively, for example, laser power sources **102a-102m** and optical data devices **106a-106n** can be arbitrarily mounted on different equipment racks, with their respective outputs and inputs coupled together (e.g., via optical power switch and tunable coupler **104**) with appropriate optical coupling (e.g., optical fiber coupling), as depicted later in **Figure 6**. In a preferred embodiment, the optical fibers conveying optical power, and conducting wires conveying electrical power and electronic signals, can be bundled together in the same cable, thus simplifying the cabling and facilitating the replacement of modules during repairs or upgrades. In any event, the arrangement, configuration and location of laser power sources **102a-102m**, optical data devices **106a-106n**, optical power switch and tunable coupler **104**, laser power monitor **108**, and data management system controller **110** in **Figure 1** are presented for purposes of illustration and description, and are not intended to

impose an architectural limitation on the present invention.

In those cases when coherent data processing or storage is required, the optical fiber that delivers the optical power can also be used to deliver light to a fiber optic coupler used to split the light at optical data devices **106a-106n** onto a plurality of fibers. The fibers at the output of the coupler can be trimmed in order to match the path length of the two resulting beams of light at the position where they interfere with each other. The resulting matched path lengths render the optical data devices more tolerant to limited coherent lengths possibly provided by laser sources **102a-102n**, and are not intended to impose a limitation on the present invention.

With reference now to **Figure 2**, a pictorial representation of an exemplary optical power switch and tunable coupler module is depicted that may be used to illustrate principles of the present invention. For example, optical power switch and tunable coupler module **200** can be used to implement optical power switch and tunable coupler **104** in **Figure 1** with power coupled from only two laser power sources (i.e., laser power sources **102a-102b**) via input connections **202a, 202b** (i.e., "m" can represent "2" in **Figure 1**). For example, 2x1 switch **204** can include at least one fiber optic switch. The fiber optic switch (or switches) can select an input connection **202a** or **202b** and thus couple the laser energy (power) present at selected connection **202a** or **202b** to an input of 1xN tunable coupler **206,** thus providing fault-tolerance

and the possibility to replace a faulty laser without interruption in the delivery of laser power and the associated down-time. Tunable coupler **206** (in combination with switch **204**), for example, can use "n-1" 1x2 fiber tunable directional couplers to direct the selected laser power received from switch **204** towards one or more optical data devices at a coupling ratio selected by laser power monitor **108**. For example, n-1 TC1400™ series tunable directional couplers (as manufactured by FiberPro) can be used to provide n tunable outputs in a known binary tree configuration. As described in more detail below, for this exemplary embodiment, a laser power monitor (e.g., laser power monitor **108** in **Figure 1**) determines the coupling ratio(s) for tunable coupler **206**.

With reference now to **Figure 3**, a pictorial representation of an exemplary, generic optical power switch and tunable coupler module is depicted that may be used to illustrate principles of the present invention. For example, optical power switch and tunable coupler module **300** can be used to implement optical power switch and tunable coupler **104** in **Figure 1** with power coupled from "m" laser power sources (i.e., laser power sources **102a-102m**) via input connections **302a-302m**.

Exemplary optical power switch and tunable coupler module **300** includes a plurality of 1xn tunable coupler sections **304a-304m**. Each tunable coupler section **304a-304m** can use, for example, "n-1" 1x2 fiber tunable directional couplers to direct the selected laser power received towards one or more optical data devices at a coupling ratio selected by a laser power monitor (e.g.,

laser power monitor **108** in **Figure 1**). Again, for example, n-1 FiberPro™ TC1400 series tunable directional couplers can be used to produce n tunable outputs in a known binary tree configuration.

For this example, each mx1 switch **306a-306n** can include at least one fiber optic switch. The fiber optic switch (or switches) can select an individual input connection from one of the tunable coupler sections **304a-304m** and thus couple the laser energy (power) present to an input of a selected device (e.g., one of optical data devices **106a-106n** in **Figure 1**) via a respective output connection **308a-308n**, without mixing light from different lasers and thus providing fault-tolerance and the possibility to replace a faulty laser without down-time. Again, for this exemplary embodiment, a laser power monitor (e.g., laser power monitor **108** in **Figure 1**) can determine the coupling ratio(s) for each tunable coupler section **304a-304m**, and which laser(s) to send optical power to each of the optical data devices by controlling switches **306a-306n**.

For coherent optical data manipulation applications (e.g., holographic data storage), it is important to prevent the (light) energy from two or more laser sources from being combined. However, in the case where coherent illumination is not required, or when the tunable coupler modules **304a-304m** are each capable of producing a tuning range that goes down to a virtually zero output power level (or at least minimal, acceptable leakage) for those optical data devices not being served, the mx1 switches **306a-306n** can be replaced with mx1 optical power combiners

(e.g., mx1 fiber couplers used as combiners) at a potentially lower cost.

With reference now to **Figure 4**, a flowchart is depicted of an exemplary process for an optical power monitor to determine a distribution of power levels for a plurality of data devices, in accordance with a preferred embodiment of the present invention. For example, referring also to **Figure 1**, process **400** can represent a process for laser power monitor **108** to determine a distribution of power levels from laser power sources **102a-102m** to optical data devices **106a-106n**. As such, for illustrative purposes only, process **400** is described herein with respect to operations of exemplary fault-tolerant, optical power management system **100** shown in **Figure 1**.

Exemplary process **400** begins by laser power monitor **108** retrieving a (device) performance priority signal from data management system controller **110** via connection **112** (step **402**). The performance priority signal from data management system controller **110** determines which optical data devices **106a-106n** have a higher performance priority, and therefore, should receive more of the available optical power. Typically, all of optical data devices **106a-106n** can be given equal priorities, and the total power available from laser power sources **102a-102m** can be distributed equally among optical data devices **106a-106n**. Additionally, the performance priority signal retrieved from data management system controller **110** can be used as a "flag" to laser power monitor **108** to recognize that an optical data device (e.g., optical data device **106a**) is

not being used (i.e., zero priority assigned by data management system controller **110**). Consequently, laser power monitor **108** can redirect laser power away from that "flagged" optical data device (e.g., optical data device **106a**) to one or more of the remaining optical data devices (e.g., optical data devices **106b-106n**).

If laser power monitor **108** receives a performance priority signal from data management system controller **110** and determines that a change in the priorities of optical data devices **106a-106n** has occurred (step **404**), laser power monitor **108** recalculates the normalized coupling ratios for the (e.g., remaining) optical data devices where the priority signal sets the weights of the normalized, weighted coupling ratios (step **406**). Laser power monitor **108** can then send an appropriate power redirection signal with the recalculated coupling ratios to optical power switch and tunable coupler **104** via connection **113**.

Next, for this exemplary embodiment, laser power monitor **108** retrieves the laser output power monitor signals from each laser power source **102a-102m** via power output monitor connections **105a-105m** (step **408**). Laser power monitor **108** can then determine whether or not a retrieved laser output power monitor signal has a value that is less than or equal to a specified power threshold value (step **410**). If so, laser power monitor **108** assumes that the particular laser power source associated with that signal is defective. Laser power monitor **108** can then send a power redirection signal (via connection **113**) to optical power switch and tunable coupler **104**, in order

to switch the defective laser power source out of service, and reapportion the power from the remaining laser power sources to optical data devices **106a-106n** (step **412**). Also, laser power monitor **108** can send an appropriate flag (e.g., fault alert message) to data management system controller **110** via connection 111, in order to initiate service to replace the defective laser power source (step **414**). Additionally, in response to receiving a fault alert message, data management system controller **110** can initiate a process to prevent a more catastrophic system failure, such as, for example, backing up system data, flushing buffers, using alternative optical data devices, etc.

Next, for this exemplary embodiment, laser power monitor **108** retrieves the power monitor signals from optical data devices **106a-106n** via respective power monitor output connections **107a-107n** (step **416**). These signals allow laser power monitor **108** to determine how much power from each laser power source **102a-102m** has arrived at a respective optical data device **106a-106n**. Additionally, the strengths of these signals can allow laser power monitor **108** to determine the optical losses due to fiber optic connections, switches, and/or couplers involved in those particular laser power flows.

In response to receipt of the power monitor signals from optical data devices **106a-106n**, laser power monitor **108** can determine whether or not a particular optical data device **106a-106n** has failed (step **418**). If so, laser power monitor **108** can send an appropriate fault alert

signal (e.g., as a flag) to data management system controller **110** via connection **111** (step **420**).

Additionally, the power monitor signals from optical data devices **106a-106n** can be used in a closed feedback process to control the coupling ratios of the tunable coupler module(s) of optical power switch and tunable coupler **104**, and to compensate for temporal fluctuations in optical power losses in the optical power distribution path. For example, laser power monitor **108** can determine from the power monitor signals received from optical data devices **106a-106n** whether or not the coupling ratios being used in the tunable coupler module(s) of optical power switch and tunable coupler **104** are correct, by comparing the power monitor signals received from optical data devices **106a-106n** with a predetermined calculation representing correct coupling ratios preferably derived from performance priority signals received from data management system controller **110** via connection **112** (step **422**). If laser power monitor **108** determines that one or more of the coupling ratios being used in the tunable coupler module(s) of optical power switch and tunable coupler **104** are incorrect, then laser power monitor **108** can send an appropriate power redirection signal to optical power switch and tunable coupler **104** via connection **113**, in order to reassign the coupling ratios (e.g., by incrementally adjusting the coupling ratios by small amounts) until the desired, correct coupling ratios are achieved (step **424**). Preferably, these incremental adjustments of the coupling ratios are designed to be small enough to prevent unstable feedback loop behavior,

but still large enough to provide a rapid system response (i.e., using control system techniques well-known to those of ordinary skill in the art).

Furthermore, the laser power monitor **108** may keep track of the periods of time, duration, and the power levels at which each of laser sources **102a-102m** are used. This information then can be used to keep track of which laser sources are most likely to fail, and preventive maintenance can be requested to data management system controller **110** via connection **111**. The preventive maintenance can be in the form of the preventive replacement of the unit, or its preventive servicing (e.g., replacement of a pump diode module). Also, the laser power monitor **108** can use the laser usage information in order to increase the useful life of each laser by using one (or both) of the following techniques: 1) by guaranteeing that each source is used at least once over a certain period of time; and 2) by equalizing the total energy output of each source by using more of those sources that have been used the least, whenever not in conflict with other data management performance priorities.

With reference now to **Figure 5**, a pictorial representation is depicted of an exemplary equipment rack containing optical data devices, optical power sources, a laser power monitor, and an optical power switch and tunable coupler, in accordance with a preferred embodiment of the present invention. For this exemplary embodiment, equipment rack **500** includes a plurality of optical data device modules **502a-502d** (e.g., including optical data

devices similar in structure and function to optical data devices **106a-106n** in **Figure 1**), a plurality of optical power source modules **504a-504b** (e.g., including optical power sources similar in structure and function to laser power sources **102a-102m**), an optical power monitor module **506a** (e.g., including an optical power monitor similar in structure and function to laser power monitor **108**), and an optical power switch and tunable coupler module **506b** (e.g., including an optical power switch and tunable coupler similar in structure and function to optical power switch and tunable coupler **104**). An optical power monitor module **506a** and a tunable coupler module **506b** can be packaged together in a single module **506** (as shown in **Figure 5**), or they can be packaged in separate modules in an alternative embodiment.

Advantageously, as shown, modules **502a-502d, 504a-504b** and **506a-506b** are mounted in the same equipment rack, with the respective outputs and inputs of modules **502a-502d, 504a-504b** and **506a** coupled together via module **506b** with appropriate optical coupling (e.g., optical fiber coupling). Also, advantageously, modules **502a-502d, 504a-504b** and **506a-506b** use similar form-factors in order, for example, to facilitate the field replacement of defective units, the upgrade of existing equipment, and the inclusion of additional equipment (e.g., more laser sources, new optical data devices, etc.). As such, a plurality of these modules can be available in order to provide the system with the redundancy required for superior fault-tolerance.

Additionally, for a preferred embodiment, the optical fibers conveying optical power between the modules shown in **Figure 5**, the conducting wires conveying electronic signals (e.g., **105a-105m** and **107a-107n**), and the conducting wires conveying electrical power to these modules can be bundled together in one cable, which simplifies the cabling and facilitates replacement of the modules during repairs or upgrades.

Furthermore, a bundle of optical cables and/or electronic signal wires and/or electrical power cable **508** can be used to interconnect equipment rack **500** to other equipment racks in a data management system.

With reference now to **Figure 6**, a pictorial representation is depicted of an exemplary data management system containing multiple interconnected racks, which are similar to the exemplary equipment rack depicted in **Figure 5**. For example, exemplary data management system **600** contains a plurality of equipment racks **602, 604, 606**. However, it should be understood that although only three equipment racks are shown in **Figure 6**, the present invention is not intended to be so limited, and data management system **600** can contain a number of additional equipment racks similar in structure and function to racks **602**, **604** and **606**. Preferably, each of racks **602, 604, 606** is arranged with modules similar in structure and function to modules **502a-502d, 504a-504b** and **506a-506b** in **Figure 5**, and coupled together (e.g., via modules similar to module **506a** in **Figure 5**), using optical cable **608** similar to cable **508**, for conveying optical power between the respective outputs and inputs of the modules with

appropriate optical coupling. Alternatively, for example, one or more of the modules (e.g., modules **502a-502d** and **504a-504b**) contained in each rack **602, 604, 606** can be arbitrarily mounted on a different one of racks **602, 604, 606**, with their respective outputs and inputs coupled together (e.g., via a module such as module **506b** in **Figure 5**) with appropriate optical coupling.

It is important to note that while the present invention has been described in the context of a fully functioning fault-tolerant, optical power management apparatus and method for automated data manipulation and storage, those of ordinary skill in the art will appreciate that the processes of the present invention are capable of being distributed in the form of a computer readable medium of instructions and a variety of forms and that the present invention applies equally regardless of the particular type of signal bearing media actually used to carry out the distribution. Examples of computer readable media include recordable-type media such a floppy disc, a hard disk drive, a RAM, CD-ROMs, and transmission-type media such as digital and analog communications links.

The description of the present invention has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to best explain the principles of the invention, the practical application, and to enable others of

ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.